and even parity. Flammersfeld[8] has shown that there is an excited state of Rb^{84} having a half-life of 23 min and emitting internal conversion electrons whose energy is approximately 0.320 Mev. Recent experiments in this laboratory[9] have delineated the excited states of Rb^{84} more exactly. The results of this investigation are shown for completeness in Fig. 9. The governing metastable state was found to have a half-life of 21 min.

It appeared difficult to reconcile the original decay scheme of Langer and Duffield[7] for Br^{84} with that proposed here for Rb^{84}. When the results of the present experiments became known, Dr. Langer and Dr. Duffield[10] measured the gamma-rays from Rb^{84} with the help of a scintillation spectrometer. Their results show a strong gamma-ray of energy 0.890 Mev and a weaker one of energy 1.89 Mev. It is now believed that the original decay scheme was incomplete and that the highest energy beta-ray group does not lead to the ground state, as originally supposed, but to an excited state from which the gamma-ray at 0.890 Mev is emitted.

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[8] A. Flammersfeld, Z. Naturforsch. **5a**, 687 (1950).
[9] R. S. Caird and A. C. G. Mitchell (to be published).
[10] The authors are indebted to Dr. L. M. Langer for communicating to them the results of their experiments.

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Total Neutron Cross Section of Sodium*

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The total neutron cross section of sodium has been measured over the energy range 120 to 1000 kev using resolutions of 2.5 to 5 kev. A number of resonances, corresponding to excited states in the compound nucleus Na^{24} were investigated. In some cases it is possible to assign J and l values and to compute the effective level spacings D_J^l. Evidence is given to show that the D_J^l, which are a measure of the complexity of a state, differ by a factor of 8 for two states of the same type and at approximately the same excitation energy (7.5 Mev) in the Na^{24} nucleus. An anomalous S-wave resonance at 300 kev suggests that the potential scattering may be spin dependent.

INTRODUCTION

THE recent good resolution work on the $Na^{23}(d,p)Na^{24}$ reaction by Sperduto *et al.*[1] gives a detailed picture of the level structure of the Na^{24} nucleus up to an excitation energy of 4.6 Mev. The level structure at somewhat higher excitation energies (7.0 Mev and above) can be studied by measuring the total neutron cross section of sodium. Adair *et al.*[2] measured this cross section from 40 to 1000 kev using a resolution of 20 kev. Although they found a number of maxima, they concluded that their resolution was not adequate for any detailed interpretation. To learn more concerning these virtual levels we have measured the cross section using resolutions of 2.5 to 5 kev.

EXPERIMENTAL METHOD

The experimental procedure for measuring the total neutron cross section was similar to that previously described.[3] Monoenergetic neutrons were produced by allowing protons of well-defined energy from the Rockefeller electrostatic generator to strike thin targets of lithium. The original proton-recoil counter was replaced by a new counter with an o.d. of 1 inch, effective length of 4 inches and 2-mil center wire, filled to 5 atmospheres of hydrogen gas and operated with 3.5 kev on the center wire. This counter was approximately twice as efficient and had a better signal-to-noise ratio. The ambiguity caused by the presence of the second group of neutrons from the $Li(p,n)$ reaction at energies above 640 kev was removed, as before, by adjusting the bias to make the counter insensitive to the lower energy group.

A metallic sodium scatterer, one inch in diameter and 0.186×10^{24} nuclei/cm^2 thick, was encased in a thin-walled (5 mil), air-tight steel cylinder. The scatterer and counter were placed at mean distances of 13 and 30 cm, respectively, from the target in the forward

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[1] A. Sperduto and W. W. Buechner, Massachusetts Institute of Technology Progress Report LNSE (1952) (unpublished); Phys. Rev. (to be published).
[2] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).
[3] Hinchey, Stelson, and Preston, Phys. Rev. **86**, 483 (1952).

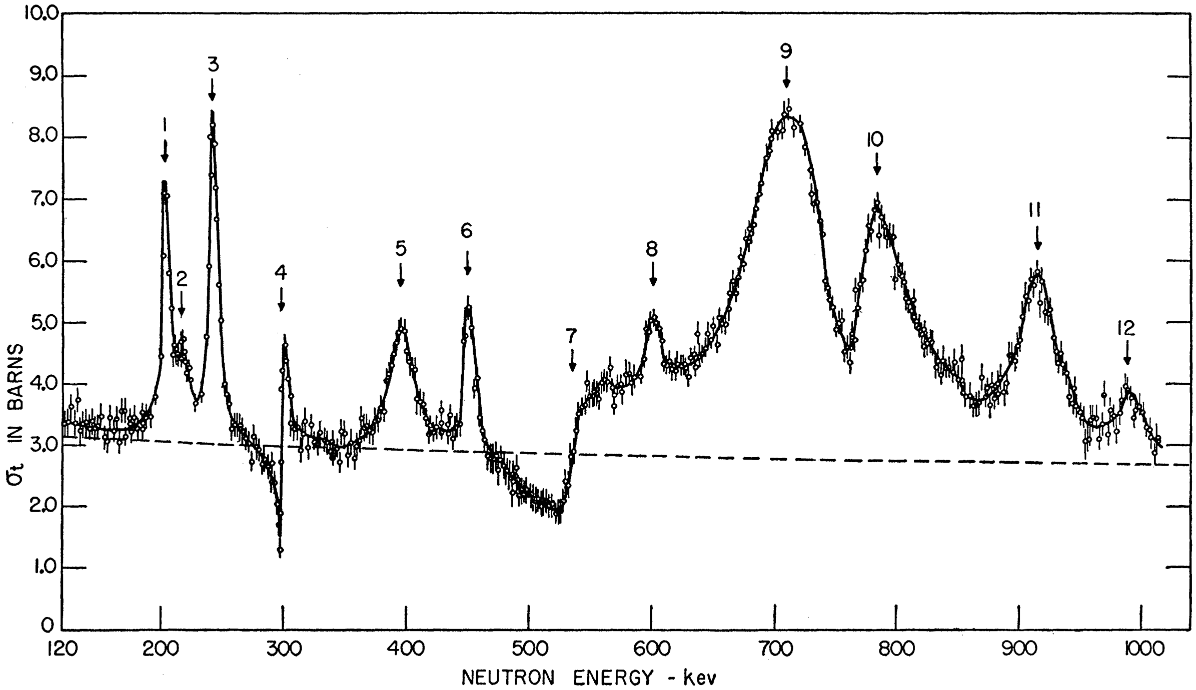

FIG. 1. Total neutron cross section of sodium. The dashed curve is the calculated potential scattering for an interactive radius of 5.1×10^{-13} cm.

direction. With this geometry, the scattering-in correction to the cross section is calculated to be approximately $7.0\times10^{-3}g\sigma$ barn, where σ is the cross section and g is the ratio of the differential scattering cross section in the forward direction to the average value. The value of g, although unknown, should not differ markedly from unity. The correction is therefore of the order of one percent. We have not applied the scattering-in correction since it is not precisely calculable and since it is less than the statistical error.

For total neutron cross section measurements, the energy resolution depends on the energy spread of the incident protons, the target thickness, and the angle subtended by the neutron detector. For our experimental arrangement, with resolutions of 2.5 to 5 kev, the principal contribution to energy spread is the target thickness. The target thickness was determined by measuring the sharp resonance at 585 kev in the total neutron cross section of sulfur.[4, 5]

The resulting curve of the total neutron cross section of sodium for the neutron energy range 120 to 1000 kev is shown in Fig. 1. In this energy range 12 resonances were observed. Not all of the experimental data are shown in Fig. 1; the resonances in the range 120 to 500 kev were measured several times. Data for each resonance have been listed in Table I. Column 2 gives the resonance energies in the laboratory system, corrected for target thickness. In the case of S-wave resonances, where the position of the maxima is shifted appreciably by interference with potential scattering, the resonance energy was determined by fitting a theoretical curve.

Columns 3, 4, and 5 give, respectively, Δ, the resolution with which the resonance was measured; Γ_M, the measured width; and Γ, the natural width calculated from the relation $\Gamma^2=\Gamma_m^2-\Delta^2$. This does not apply to resonance 4, a narrow S-wave resonance, which is discussed below.

In column 6 we list the experimentally determined values of the cross section for the resonances. In the case of resonances excited by S-wave neutrons, this is taken as the difference between the maximum and minimum values. For other resonances the value is taken as the height of the maximum value of σ_T above the estimated "background" level. Column 7 lists the values obtained after corrections have been applied to take account of the finite value of the resolution employed.

DISCUSSION

A. J Value Assignments

When the predominant interaction of neutrons with the nucleus is elastic scattering, a comparison of the measured value of the total resonance cross section with the predictions of theory permits the assignment of total angular momentum J. If the possibility exists

[4] Peterson, Barschall, and Bockelman, Phys. Rev. **79**, 593 (1950).

[5] If the measured width of the sulfur resonance is Γ_M, then $\Delta E_n=(\Gamma_m^2-\Gamma^2)^{\frac{1}{2}}$ where we take $\Gamma=1.5$ kev. From ΔE_n we calculate ΔE_p. From the knowledge of the variation of stopping power we obtain ΔE_p at other proton energies and then convert to ΔE_n, the resolution at corresponding neutron energies.

of other processes, such as (n,p), (n,α) or inelastic scattering, only a lower limit can be placed on J. In the present case, the (n,p) and (n,α) reactions are eliminated because they have large negative Q values. A decision as to whether inelastic scattering can occur depends on the knowledge of low-lying levels in the target nucleus. This region of sodium has been studied by the measurement of α-particles from the $Mg^{25}(d,\alpha)Na^{23}$ reaction[6] and by the observation of γ-rays resulting from inelastic proton scattering on Na^{23}.[7] Both experiments indicate a first excited state in sodium at 430 kev. This limits the assignment of definite J values to the first six resonances. These assignments are listed in column 9; the theoretical values of the cross section are given in column 8.

The agreement between experimental and theoretical values of the cross section is reasonable for resonances 1, 2, 4, and 6. Resonances 3 and 5 show unusually poor agreement. The experimental value for No. 3 is 1.5 barns high for $J=1$ and 1.3 barns low for $J=2$, while No. 5, which is a fairly broad symmetrical resonance, is 0.6 barn low for $J=1$ but 1.2 barns high for $J=0$. The differences are larger than our estimated experimental errors.

The computed values of the cross section for the case of purely elastic scattering are listed also for resonances 7 to 12. Since these resonances can give rise to inelastic scattering, the values serve only as lower limits for J. For example, resonance No. 11 has a measured cross section of 2.3 barns, indicating that J is at least 3. If No. 9 is a single resonance, the J value must be at least 5 which would require excitation by neutrons with 3 or more units of orbital angular momentum. It is probable that this peak is, instead, a superposition of at least two noninterfering states (i.e., states of different J or parity).

TABLE I. Summary of data relating to the neutron resonances in the total cross section of sodium. Energies are expressed in kev and cross sections in barns. Column 2 gives the resonance energies in the laboratory system. Columns 3, 4, and 5 give, respectively, Δ, the resolution with which the resonance was measured; Γ_M, the measured width; and Γ, the natural width. Column 6 lists the measured resonance cross sections; column 7, the cross section after applying corrections for resolution. Column 8 lists the theoretical values of the cross section for the corresponding J values listed in column 9. Column 11 lists the calculated values of $D_J{}^l$ for the corresponding values of l listed in column 10.

No.	$(E_R)_{lab}$	Δ	Γ_M	Γ	σ	σ^*	σ_{cal}	J	l	$D_J{}^l$
1	204	4.1	6.5	5	3.9	5.2	5.22	1	1	450
2	217	4.0	~14	~14	~1.3	~1.3	1.63	0	1	1150
3	243	3.8	8	7	5.0	5.9	4.38	1	1	480
							7.32	2		
4	297	3.6		4	3.4		3.57	1	0	67
		2.4		4	3.5					
5	396	~5	23	23	2.0	2.1	2.69	1	1	950
6	451	~5	10	9	2.2	2.5	2.37	1	1	320
									2	4000
7	542	~5		39	2.1		(2.0)	(1)	(0)	(520)
8	602	~5	~8	~6	1.1	1.4	(1.8)	(1)		
9	710	~5		72	~5.3		(5.5)	(5)		
10	784	~5		38	~2.6		(2.3)	(2)		
							(3.1)	(3)		
11	914	~5		36	~2.5		(2.7)	(3)		
12	988	~5		24	~1.0		(1.0)	(1)		

[6] Endt, Haffner, and Van Patter, Phys. Rev. **86**, 518 (1952).
[7] Stelson, Preston, and Goodman, Phys. Rev. **86**, 629 (1952).

B. Average Level Spacing, $D_J{}^l$

Theory suggests that the natural neutron width Γ_n be expressed as a product:

$$\Gamma_n = T_n{}^l D_J{}^l / 2\pi,$$

where $T_n{}^l$ is the probability that the incoming neutron will penetrate the centrifugal barrier and enter the nucleus. The $T_n{}^l$ are readily calculable and, therefore, if the l value of the neutrons producing the excitation is known, one can compute the interesting quantity $D_J{}^l$. The reciprocal of $D_J{}^l$ is a measure of the inherent nuclear lifetime; large values of $D_J{}^l$ ($\sim$25 Mev for sodium) would suggest an interaction similar to a simple single-body interaction. The degree to which $D_J{}^l$ is less than this large value is a measure of the complexity of the state.

The potential scattering in the energy range investigated is small for neutrons having $l \geqslant 1$. Therefore, only resonances excited by S-wave neutrons show strong interference with potential scattering. This identifies the narrow resonance No. 4 as an $l=0$ resonance. The computed $D_J{}^l$ value is 67 kev. Resonance No. 7 is also excited by $l=0$ neutrons, but here the resonance energy is a little above the threshold for inelastic scattering. On the basis of purely elastic scattering, the two possible values for the resonance cross section are 1.92 and 3.18 barns for $J=1$ and 2, respectively. If the resonance were $J=2$, fairly strong inelastic scattering would be required to reduce the cross section to the experimental value of 2.1 barns. For this resonance, strong inelastic scattering is quite unlikely since the inelastic neutrons, having only 90 kev and an unknown l value, must compete with the outgoing elastic neutrons of 520 kev and $l=0$. On the other hand, the experimental value of 2.1 barns agrees reasonably well with the $J=1$ value for purely elastic scattering. If this interpretation is correct, i.e., that the resonance is mainly an elastic scattering resonance, we obtain a $D_J{}^l$ value of 520 kev. We have, then, evidence that in the Na^{24} nucleus at approximately the same excitation energy (7.5 Mev), two levels of the same type ($J=1$ and even parity) can differ in $D_J{}^l$ values by a factor of 8.

The resonances 1, 2, 3, 5, and 6 do not exhibit appreciable interference with the potential scattering, indicating that the excitation is by neutrons with l values larger than zero. For these resonances there is no straightforward method of determining the l value. Hence, the $D_J{}^l$ values are somewhat speculative. In addition, even if the l values were definitely known, the D_J cannot be as precisely determined as one proceeds to larger l values because the $T_n{}^l$ become increasingly sensitive to the value of the interaction radius R about which there is considerable uncertainty. For our calculations of the $T_n{}^l$ we have chosen $R=5.1\times10^{-13}$ cm. This is approximately midway between the values given by the expressions $1.5\times10^{-13}A^{\frac{1}{3}}$ and $1.5\times10^{-13}[A^{\frac{1}{3}}+1]$.

The calculated potential scattering for $R=5.1\times10^{-13}$ cm is shown in Fig. 1 by the dashed curve.

The possibility of resonance excitation by neutrons with sufficiently large l values can be eliminated because the resulting $D_J{}^l$ values are impossibly large, i.e., they exceed the Wigner limit. If it is assumed that the resonances 1, 2, 3, and 5 are excited by $l=2$ neutrons, the calculated $D_J{}^l$ (15 to 40 Mev) are approximately equal to the Wigner limit. Although not definitely excluded, such large D_J values seem unlikely, especially in view of the two $D_J{}^l$ values derived from the $l=0$ resonances, and we have therefore assigned $l=1$ to these resonances. However, one should be cautious with this argument as it may lead to an artificial uniformity in $D_J{}^l$. Resonance 6 yields $D_J{}^l$ values of 320 kev or 4 Mev for $l=1$ or 2, and either assignment seems acceptable. The l assignments and corresponding $D_J{}^l$ for the resonances are listed in columns 10 and 11 of Table I.

C. Spin Dependent Potential Scattering

Although the resonance cross section of the narrow S resonance, No. 4, given by the difference $\sigma_{\max}-\sigma_{\min}$, agrees well with the theoretical value for J=1, the absolute values of the maximum and minimum cross sections are not in good agreement with theory. From the statistical theory we have the result that the depth of the minimum is a fraction g of the total potential scattering,[8] where g is the statistical weight factor $(2J+1)/2(2I+1)$. Enlarged plots of data taken with 3.6- and 2.4-kev resolutions are shown in Fig. 2. The dashed curves in the figure are calculated from the theory (for infinitely good resolution) where we have taken the natural width as 4.0 kev and the total potential scattering σ_P as 3.0 barns. It is seen that, even with the finite experimental resolutions, the interference dip has considerably more depth than predicted by theory.

On first thought one might be tempted to match the experimental value of $\sigma_{\min}$ by reducing the value of the total potential scattering; a reduction to 2.4 barns is required. There are two arguments against this. First, as is seen in Fig. 1, the larger value, calculated for an interaction radius of 5.1×10^{-13} cm, seems to be reasonable throughout the energy range measured. In addition, it is in good agreement with other experimental data at lower energies. Second, while reducing the value of σ_P to 2.4 barns yields the correct $\sigma_{\min}$, the actual depth of the interference dip is predicted to be only 0.9 barns, which is considerably less than is indicated by the experimental curve.

A similar anomalous situation in sodium has been observed at lower neutron energies. Hibdon *et al.*[9] found a neutron scattering resonance at 3 kev, which has a resonance cross section of 550 barns ($J=2$) and a width of 170 ev. However, there is no discernible

[8] This is true only if, as in the present case, l values larger than zero are negligible contributions to the total potential scattering.

[9] Hibdon, Muehlhause, Selove, and Woolf, Phys. Rev. **77**, 730 (1950).

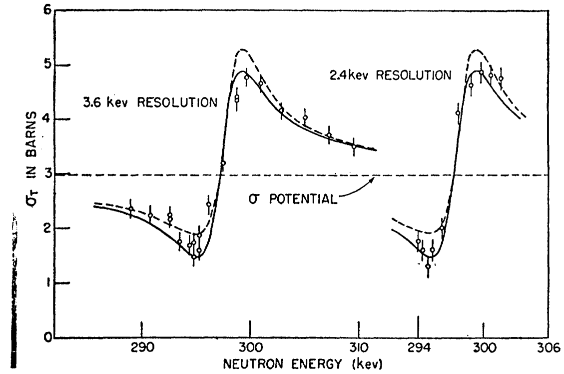

FIG. 2. Plots of data taken for the narrow S resonance, No. 4. The dashed and solid curves are calculated for the cases $\sigma_-/\sigma_+=1$ and $\sigma_-/\sigma_+=2$, respectively. The natural width and the total potential scattering are taken as 4.0 kev and 3.0 barns, respectively.

interference dip characteristic of $l=0$ excitation. Selove[10] has interpreted this as an indication that the S-wave potential scattering is strongly spin dependent. He finds $\sigma_-/\sigma_+=11$, where σ_+ and σ_- are the potential scattering cross sections for the + and − spin states. In this notation the total potential scattering σ_P equals $\frac{3}{8}\sigma_-+\frac{5}{8}\sigma_+$. This view also yields a consistent interpretation of the coherent scattering cross section of sodium measured by Shull and Wollan.[11,12]

Therefore, invoking spin dependent potential scattering to account for the unusually strong interaction of the S resonance at 300 kev, we have calculated the theoretical curve for the case $\sigma_-/\sigma_+=2.0$ (for infinitely good resolution) where, again, the natural width is taken as 4.0 kev and σ_P as 3.0 barns. These curves, giving a better fit, are shown in Fig. 2 by the solid line. However, even with the assumption of spin dependence, the actual shape of the experimental curve is not well represented by the calculated curve; the experimental points give a noticeably sharper interference dip.

The second S resonance, No. 7, gives a good fit with the assumption that the potential scattering is not dependent on the spin state. If these interpretations are correct, we have the result that the potential neutron scattering in sodium is strongly spin dependent at low energies, $\sigma_-/\sigma_+=11$ at 3 kev, reducing to a factor of 2.0 at 300 kev and becoming approximately 1 at 550 kev.

In conclusion we wish to express our appreciation to Mr. I. E. Slawson and Mr. D. C. Thompson for invaluable help with the Rockefeller generator.

[10] W. Selove, Phys. Rev. **80**, 290 (1950).

[11] C. G. Shull and E. O. Wollan, Phys. Rev. **81**, 527 (1951).

[12] The absence of a dip might also be explained by the assumption that even at this low neutron energy the excitation is due to P wave neutrons. In this connection it is interesting to calculate the $D_J{}^l$. Taking $R=5.1\times10^{-13}$ cm we find $D_J{}^l$ is 25 kev for S-wave and 6 Mev for P-wave neutrons. The 25-kev value is small, but it is not very different from the 67-kev value for resonance No. 4, while the 6-Mev value is large but certainly not impossibly large. The measurement of the angular distribution of the neutrons scattered by this resonance, if practicable, would probably decide the question of S-wave *vs* P-wave excitation.